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Modelling of part distortion due to residual stresses relaxation: An aeronautical case study

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Abstract

Metallic parts for the aeronautics industry are usually manufactured by material subtraction using machining processes. The gradual relaxation of the bulk material residual stresses during machining causes distortion in the final part. When modelling a multi-pass machining process, in order to predict distortion, the classical finite element method, using conforming meshes, faces limitations in flexibility and accuracy. Cutting paths cannot match the work-piece mesh before the simulation, since they are defined in the initial geometry and not in a deformed one. As a result, re-meshing is required between two machining passes. In order to circumvent these limitations, an innovative approach based on the level-set method has been developed in order to define cutting paths independently of the work-piece mesh. The proposed approach is applied to simulating milling of an airfoil.

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Keywords: Residual stresses; Machining; Simulation

1. Introduction

Part distortion due to residual stress is an ongoing recurring manufacturing challenge in machining of large aerospace components which causes unexpected non-conformance parts, rework cost and delays. Residual stresses are defined as mechanical stresses in a solid body, which is currently not exposed to forces or torques and has no temperature gradients [1]. In general, residual stresses can be classified in two main groups. The first one, inherent residual stresses, refers to the stresses induced during the material manufacturing from various processes such as melting of alloys, casting, rolling, quenching and stretching. The second one, machining induced residual stresses, refers to the stresses introduced during machining due to the thermo-mechanical nature of the process. Indicatively, grind-hardening induced residual stresses have been recently investigated [2] [3]. Both these groups can lead to significant dimensional instability through distortion but also to un-predictable mechanical performance, as residual stresses can be both compressive and tensile affecting the mechanical properties of the final part. So far, the aerospace industry sector utilizes extra manufacturing processes to confront distortion, such as shot peening, which is a cold mechanical process used to generate compressive residual stresses layers by modifying the mechanical properties and the shape of aerospace components. However, this strategy lacks efficiency, as it is based on the operator's experience and if the part is not conformed after 5 cycles of shot peening is then rejected, leading to increased scrap rate and cost. A study by Boeing, based on four aircraft programmes, estimated the rework and scrap costs related to part distortion, which were found to exceed the amount of 290 million dollars [4]. In another research, it was estimated that part distortion causes an economic loss of 850 million euros per annum to the German automotive, machine tool and power transmission industries [5].

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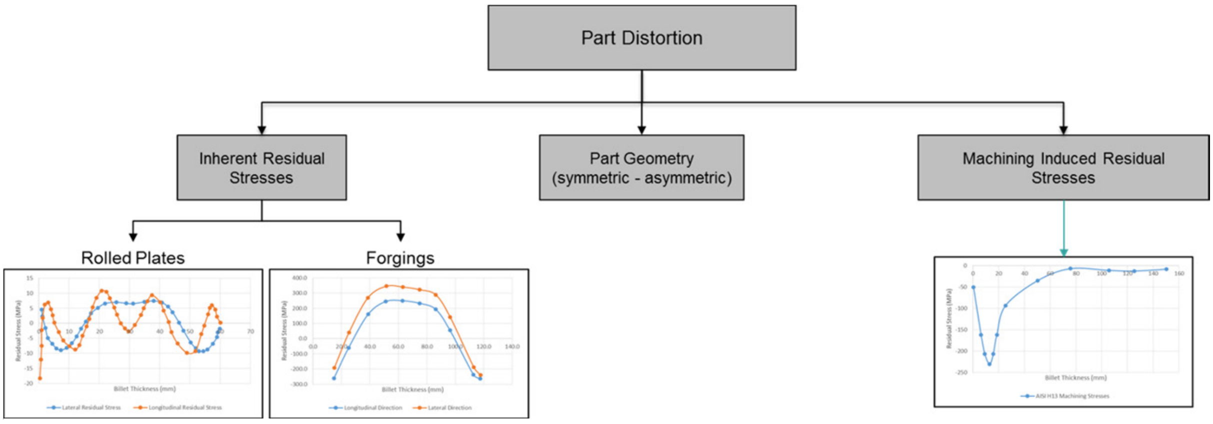

Fig. 1. Part distortion crucial factors.

It is obvious that part distortion is an issue of significant importance for the manufacturing community and especially for the aerospace industry. In [6] the crucial factor for distortion in aerospace parts are clearly described and can be summarized in Fig. 1. The demand of increased fuel efficiency in aircrafts has led to the design of thin wall components, which are manufactured after removing 90%-95% of the bulk material. When machining away such large portions of the bulk material, inherent residual stresses are relaxed and a new distribution of stresses in the part is created. This re-distribution leads to a new equilibrium of the part's stress state and distorts its final shape.

Utilizing numerical tools for part distortion modelling can change the manufacturing paradigm from retro-active (shot peening) to pro-active (distortion prediction). A lot of researchers have focused on part distortion modelling. The majority of these studies uses the finite element method. In [7] and [8] an explicit dynamic, coupled thermo-mechanical finite element model, using a Lagrangian FEM approach with adaptive re-meshing to resolve multiple length scales (i.e. cutting edge radius, cheap load etc.), tool - work-piece interaction and transient thermal field, is described. Both inherent and machining induced residual stresses were considered, leading to the conclusion that both type of stresses, as well as the part position in the billet have significant effect on the final distortion.

In [9] a hybrid model consisting of 3 sub-models was developed. Each of the 2 sub-models consisted of a linear regression model and a finite element model. The regression models were used to determine process specific boundary conditions for the FE simulation, which were used to calculate shape deviations. The regression models contained analytical equations for each boundary condition required. However the coefficients in each equation must be determined experimentally. The third sub-model receives as input the geometrical data from the previous ones and constitutes the final hybrid model. It is obvious that modelling of distortion is a computationally intensive task, especially when taking into account both machining induced and inherent residual stresses. As a result, the need to understand which type of stress (i.e inherent or machining induced) becomes dominant regarding distortion in the case studied, is generation. In [10] clear guidelines are described for this issue. Specifically, it can be said that inherent residual stress is the dominant factor for distortion in parts of over 4 mm thickness. On the other hand, when feed per tooth exceeds the value of 0.35 mm/tooth the machining induced stresses take over and become the dominant factor.

These guidelines were validated with full-scale experiments. Taking these into account, distortion modelling can be simplified and due to the fact that most aerospace parts are more than 4 mm thick, distortion can be expressed as a problem of inherent stresses. This approach was implemented in [11]. A simulation-based system was described for pro-actively addressing distortion. The modelling methodology did not take into account the machining induced stresses, as all the material removal was done in just one pass and realistic milling was not simulated. As a result, the computational time was radical decreased without losing substantial accuracy. However, this methodology can improve its accuracy if it would take in account the gradual residual stress relaxation from the multi-pass material removal process. On the other hand, in that case, the computational time would be increased due to the fact that a re-meshing would be needed between two consecutive passes. This is because cutting paths cannot be defined within the work-piece mesh just once before the simulation. Each path requires a re-mesh of the machined work-piece geometry as it needs to match the final geometry. At this point, level set theory [12], can be used and can overcome this problem. The level set is a signed distance function defined at the nodes of the finite element mesh and it is commonly used to represent material interfaces, holes, cracks, etc. [13,14], so that the boundaries can go through elements.

The aim of the current study is to demonstrate an efficient numerical methodology for part distortion modelling for aerospace parts. This methodology, as depicted in Fig. 2:

- Takes into account the inherent residual stresses which are the dominant factor for distortion in our case.
- Simulates the gradual relaxation of residual stresses after a machining pass.
- Uses the level set method for cutting paths (material removal sequence) representation.

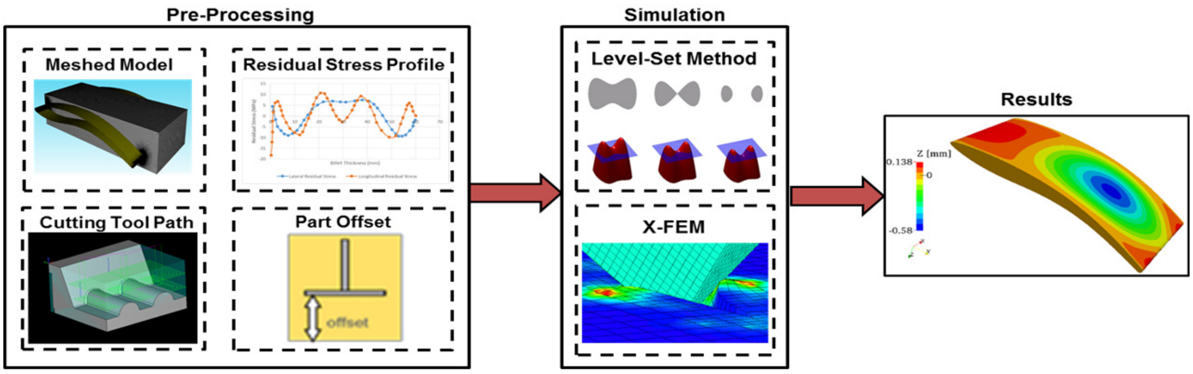

Fig. 2. Proposed modelling methodology.

In order to reduce the computational time the multi-pass machining process is not simulated as a thermo-mechanical phenomenon but as a simultaneous material removal process in each pass. However, the cutting paths, which represent the material removal sequence in each pass, have been taken into account in order to understand the effect of inherent residual stresses relaxation. The methodology is tested on a typical aerospace part, an airfoil and the results are presented.

2. Modelling Methodology

As described above, a machining distortion prediction methodology, which takes into account the inherent residual stresses of the part, has been developed. The machining process is modelled as multi-pass. Each pass is modelled to be performed in a single time-step. Thus the machining process is not modelled as a thermo-mechanical phenomenon. In general the required input from the user are:

- The Poisson's ratio and Young's modulus of the material. The material can be considered as linear elastic given the magnitude of inherent residual stress (10-30 MPa for aluminium rolled plates).
- The inherent residual stresses profiles of the billet which can be obtained experimentally [11] and are used as input to our approach. The basic assumption behind the simulation strategy is that residual stresses are homogenous in the plane of product. This means that if residual stresses are measured on the one end of the plate, it should be exactly the same as the other one. This assumption is generally true for rolled plates but not for forged billets. Additional attention must be taken to measure outside of the homogenous zone near stretcher jaws [11].
- The geometry of the final part and also of the billet, which have to be meshed using tetrahedron elements. As the model has been developed for methodology demonstration purposes, systematic finite element model development, with the execution of convergence tests, has not been followed.
- The boundary conditions are just sufficient to block rigid body motion. This means that real boundary conditions, which are applied during milling are not reproduced in the solving code. In these circumstances, this is not necessarily a problem, because all the material removal for each pass is being performed in a single-step and real milling is not simulated [11].
- The next step is to define the offset of the part inside the billet which is one of the dominant parameters for part distortion along with the cutting tool path [6].

In order to reduce the computational effort, which is a main issue, eXtended Finite Element Method (XFEM) had been used. The core of XFEM is the integration of the level set method.

FE modelling using conforming meshes faces major limitations. Large element distortions at the chip formation zone generate the need for re-meshing after each machining pass. In order to circumvent those limitations, the proposed methodology makes use of the level set method for the simulation of the machining process. The level set method was introduced by Osher and Sethian [12] in the late 1980's. In three dimensions, the level set is essentially a function φ that takes a zero value on the boundary of a surface S, as shown in the equation below:

$$S = \{(x, y, z) \mid \varphi(x, y, z) = 0\} \quad [1]$$

The level set function φ is positive at all points (x, y, z) lying on one side of the surface S, and negative for those lying on the other side. Using this method, we can define the boundary surface between the volume of material to be removed by machining, and the volume of material that is retained. During the simulation, all the material lying outside this boundary is removed. As the level set surface cuts across the volume of the elements intersecting with the surface, only the layer at the surface needs to be re-meshed.

For machining applications one level-set is used to represent one machining path. Shape function enrichment is not needed given the fact that we are interested only on the results on one side of the level-set. The level-set is computed as the smallest distance with respect to the cutting tool path, a sign given according the side of the cutting tool path. During machining operation, inherent residual stresses are re-equilibrated around the newly created interface, which leads to undesired displacements. In order to represent this phenomenon, internal forces are computed and applied in the opposite direction along the level-set in order to satisfy the equilibrium equation along a free surface. At the end of each pass, nodal positions of the mesh are updated according to the displacement field. On this new configuration, a new level-set field is computed according to the next cutting tool path which is defined in the initial configuration. In case the boundary conditions remain the same between two passes, nothing special is done, but if a boundary condition does not apply anymore, an additional computation step is performed, before the mesh update, in order to take it into account.

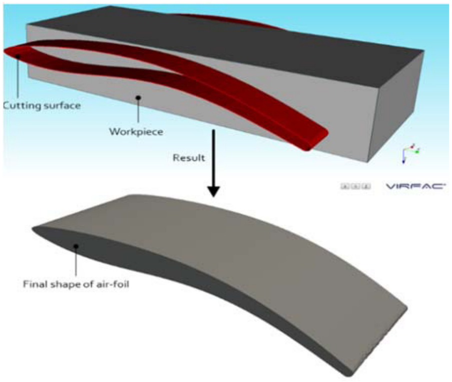

Fig. 3. Airfoil and billet geometry.

3. Case Study

In order to test the modelling methodology a typical aerospace part, an airfoil, has been selected. The part's dimensions are 500 mm, 200 mm, 50 mm and the billet's dimensions are 600 mm, 200 mm and 60mm thickness. Aluminum 2024 T3 was selected as the material for this case study. Due to the fact that the analysis is linear – elastic the only material properties needed are the Young Modulus and Poisson's Ratio which are 73.1 GPa and 0.33 respectively. The geometry of the airfoil and billet are presented in Fig. 3.

The residual stress profiles of the billet can be seen in Fig. 4 and they have been obtained experimentally using the slitting method [11]. A detailed presentation of the experimental values is performed in Table 1.

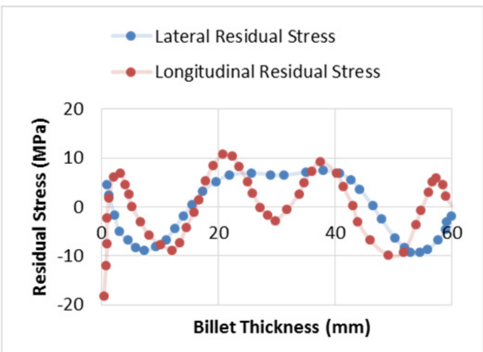

Fig. 4. Billet's residual stresses profiles

Regarding meshing strategy, both the billet and the cutting area have been meshed with tetrahedral elements. A dense mesh was applied to the edges of the airfoil in order to adequately capture highly non-linear regions and a coarse mesh to the rest of the model, as illustrated Fig. 5.

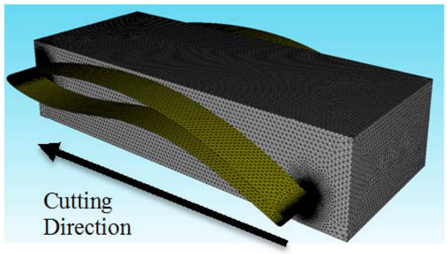

Fig. 5. Meshed Model

In total 465768 elements were used. The part offset was selected at 3mm from the bottom of the billet and the cutting direction is parallel to the long axis of the part.

4. Results

In Fig. 6. the distortion analysis results are presented. The methodology can predict both in-plane and out-of plane distortion. The distortion magnitude and distribution is reliable according to state-of-art results and the part dimensions [6]. The largest distortion values 0.922 mm are observed in the Y-direction, as reasonably expected since the cutting direction of the tool was on the same direction and therefore had a major effect. Moreover, as it can be observed in Fig. 6 the distortion results are symmetrical due to the fact that the inherent residual stresses profiles are also symmetrical.

a.

b.

c.

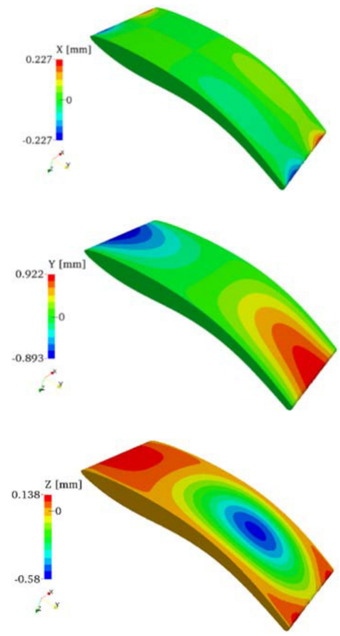

Fig. 6. Distortion Results a, (x direction), b (y direction) c (z direction).

Table 1. Experimental data for the inherent residual stresses of the Al2024 T3 billet.

Lateral Direction		Longitudinal Direction	
Thickness (mm)	Stress (MPa)	Thickness (mm)	Stress (MPa)
0.90	4.52	0.90	-12.06
1.20	2.37	1.20	1.79
2.00	-1.62	2.00	6.22
3.00	-4.90	3.00	6.88
4.00	-6.79	4.00	4.62
5.00	-8.35	5.00	-2.92
7.00	-8.95	7.00	-5.75
9.00	-8.14	9.00	-7.63
10.00	-6.64	10.00	-7.26
12.00	-4.33	12.00	-4.15
13.00	-1.85	13.00	-1.04
15.00	0.51	15.00	1.41
17.00	3.31	17.00	5.37
19.00	5.13	19.00	8.48
21.00	6.58	21.00	10.74
25.00	6.95	25.00	10.46
28.00	6.62	28.00	5.18
31.00	6.51	31.00	2.83
34.00	7.10	34.00	0.00
38.00	7.47	38.00	-2.73
40.00	6.93	40.00	-0.57
42.00	5.53	42.00	2.73
44.00	3.69	44.00	7.35
46.00	0.25	46.00	9.33
47.00	-2.45	47.00	6.97
50.00	-6.33	50.00	4.24
51.00	-8.32	51.00	-2.92
52.00	-9.29	52.00	-6.69
54.00	-9.29	54.00	-9.80
55.00	-8.76	55.00	-9.24
57.00	-6.77	57.00	-3.58
58.00	-4.62	58.00	-0.75
59.00	-3.00	59.00	3.02
59.50	-1.82	59.50	6.03
60.00	0.19	60.00	0.19

5. Discussion

Part distortion is a huge challenge in the aerospace industry. Shot peening is today's downstream solution in order to induce compressive residual stresses and correct the distortion. Unfortunately, this adds manufacturing costs and lead time to the manufacturing lifecycle [11]. An efficient methodology addressing this problem simulation wise has been developed. The methodology takes into account both inherent and machining induced stresses. Regarding the latter, the process is not modelled as a transient thermo – mechanical phenomenon, as such an approach would be computationally intensive. However the relaxation of the residual stresses due to multi-pass machining has been modelled making the assumption that the whole pass is machined simultaneously. It is an assumption that does not have a major effect, since machining induced residual stresses are observed only in the first few μm depth from the surface of the part and mainly affect the structural integrity of the part, in terms of crack initiation, and not the shape. The innovation of the methodology is the utilization of level-set method for the cutting tool path representation in the model. This saves significant computational time as a time consuming re-meshing, after each machining pass, is not needed. As far as it concerns the integration of the level set method in the model, this could not be efficiently done using the classical FEM. Therefore XFEM was used, which is a more efficient method, since it enriches the shape functions in order to model discontinuities along material interfaces. For evaluating the efficiency of the proposed method a typical aerospace part was used and the results were in accordance to state of the art [7-11].

This paper's approach can be used in the industrial workflow shown in Fig. 7. The main issue is that in the Chantzis et. al [11] workflow, the bulk material was modelled to be machined in a single step. The choice is justified for computational efficiency. However, with the utilization of XFEM and the level-set method, the performance of the workflow can be radically improved. The simulation time in this paper is 20 minutes using a 10mm step-over machining parameter. As a result it can be used as 'Design against Distortion' tool in the design and development of new aerospace parts, as it will be possible to predict the distortion behavior of any new conceptual part through simulation. Therefore, decisions on the plate thickness and material specifications can be taken earlier at the design stage.

5.

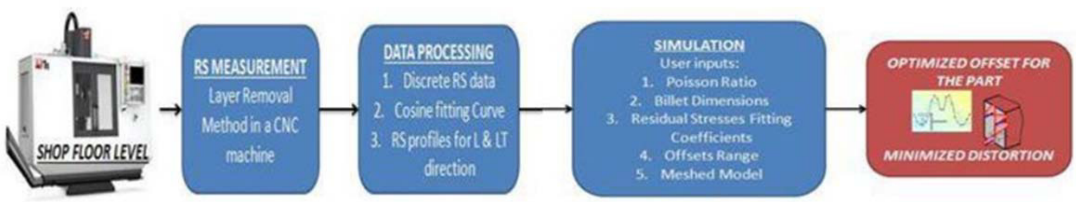

Fig. 7. Industrial workflow for minimized distortion [11].

6. Further Research

In the long run, the integration of VIRFAC to a CAx platform would increase its efficiency. G-code and intermediate machining geometries generated from a CAM software, can be directly used as input to this modelling methodology. As for the simulation strategy, further research needs to be done so realistic boundary conditions, progressive material removal and superficial residual stresses could be integrated because the proposed approach can be considered conservative for certain cases. For example, during milling, depending on the clamping, the part distortion due to clamping may be accidentally compensated by a milling pass .Finally, an experimental validation of the proposed modelling methodology needs to be done in order to investigate and improve its robustness.

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